State of the Art of Starlight Suppression Technology

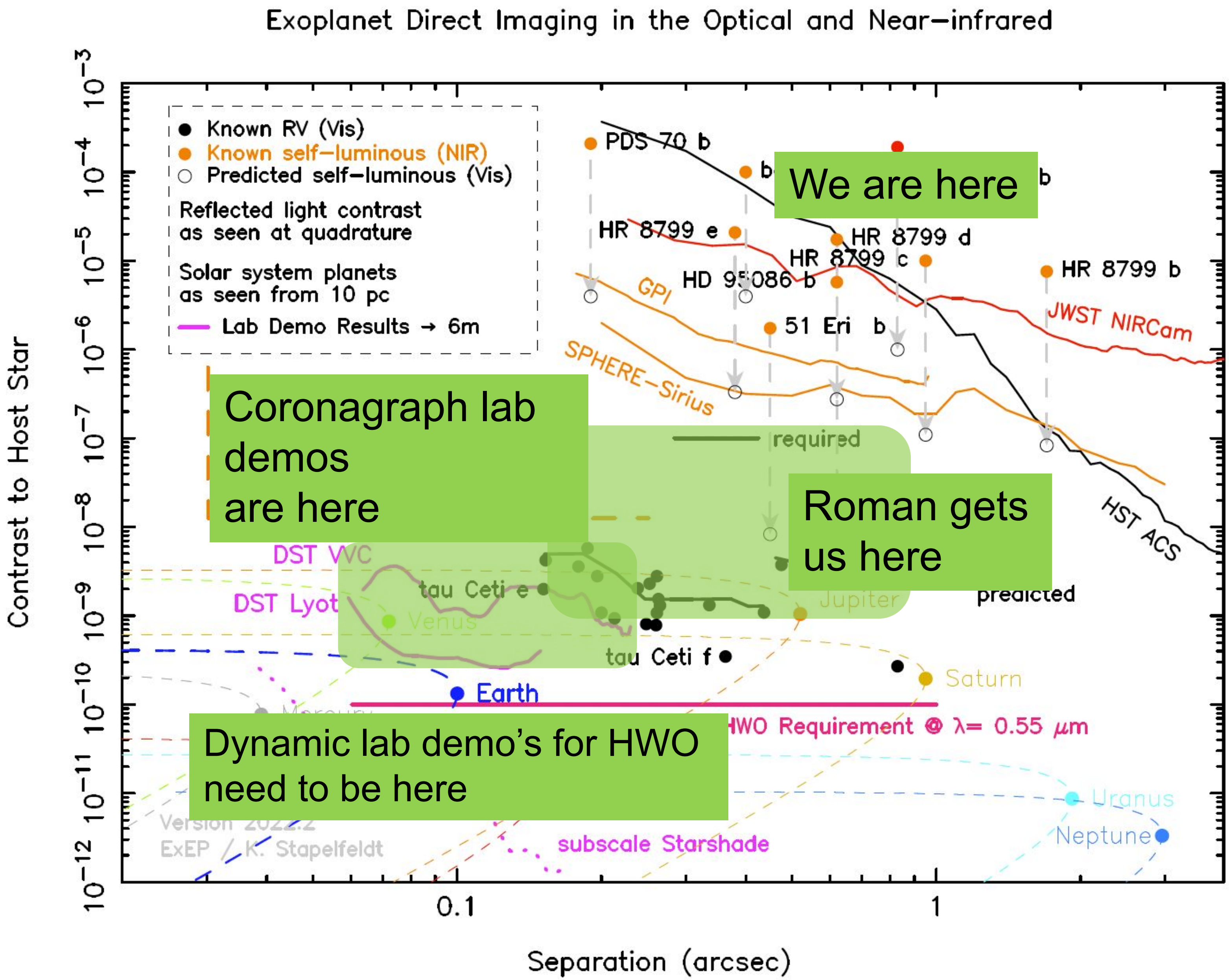
Brendan Crill, Pin Chen, Nick Siegler

NASA Exoplanet Exploration Program
Jet Propulsion Laboratory / California Institute of Technology

April 12, 2023

JPL clearance for unlimited release CL#23-0900

Requirements



Roman Coronagraph Laboratory Demonstrations

Table 2.1: Coronagraph contrast demonstrated in laboratory testbed settings by the Roman Coronagraph team. Adapted from Seo (private communication).

Year	Accomplishment	Contrast	λ (nm)	Band	Angle (λ/D)	Reference
2015	Narrowband 360° Hybrid Lyot contrast with 2 DMs and Roman pupil	6.92×10^{-9}	550		3–9	[22]
2015	Broadband Hybrid Lyot demo	8.54×10^{-9}	550	10%	3–9	[23]
2015	Broadband Shaped Pupil demo	8.80×10^{-9}	550	10%	3–9	[23]
2017	Broadband Hybrid Lyot	1.60×10^{-9}	550	10%	3–9	[24]
2017	Broadband Shaped Pupil	4.3×10^{-9}	550	10%	2.8–8.8	[24]
2017	Broadband Shaped Pupil and Hybrid Lyot dynamic environment[a]	$<1\times10^{-8}$	550	10%	3–9	[24]
2017	Integral Field Spectrograph contrast demo	1.00×10^{-8}	660	18%	3–9	[25]
2018	Broadband Disc mask contrast	3.46×10^{-9}	660	10%	6.3–19.5	[26]
2019	Band 1 Hybrid Lyot	3.58×10^{-9}	575	15%	3–9	
2020	Integral Field Spectrograph contrast demo	4.83×10^{-9}	760	18%	3–9	

[a] Sensing and control of flight-like tip, tilt, and focus aberrations only.

[22] Byoung-Joon Seo et al. *Milestone 4 Final Report: Narrowband Contrast Testbed Demonstration of Hybrid Lyot Coronagraph for WFIRST-AFTA*. https://exoplanets.nasa.gov/exep/resources/documents/ (cited on page 14).

[23] Eric Cady et al. *Milestone 5 Final Report: Hybrid Lyot and Shaped Pupil Broadband Contrast Testbed Demonstration for WFIRST-AFTA*. https://exoplanets.nasa.gov/exep/resources/documents/ (cited on page 14).

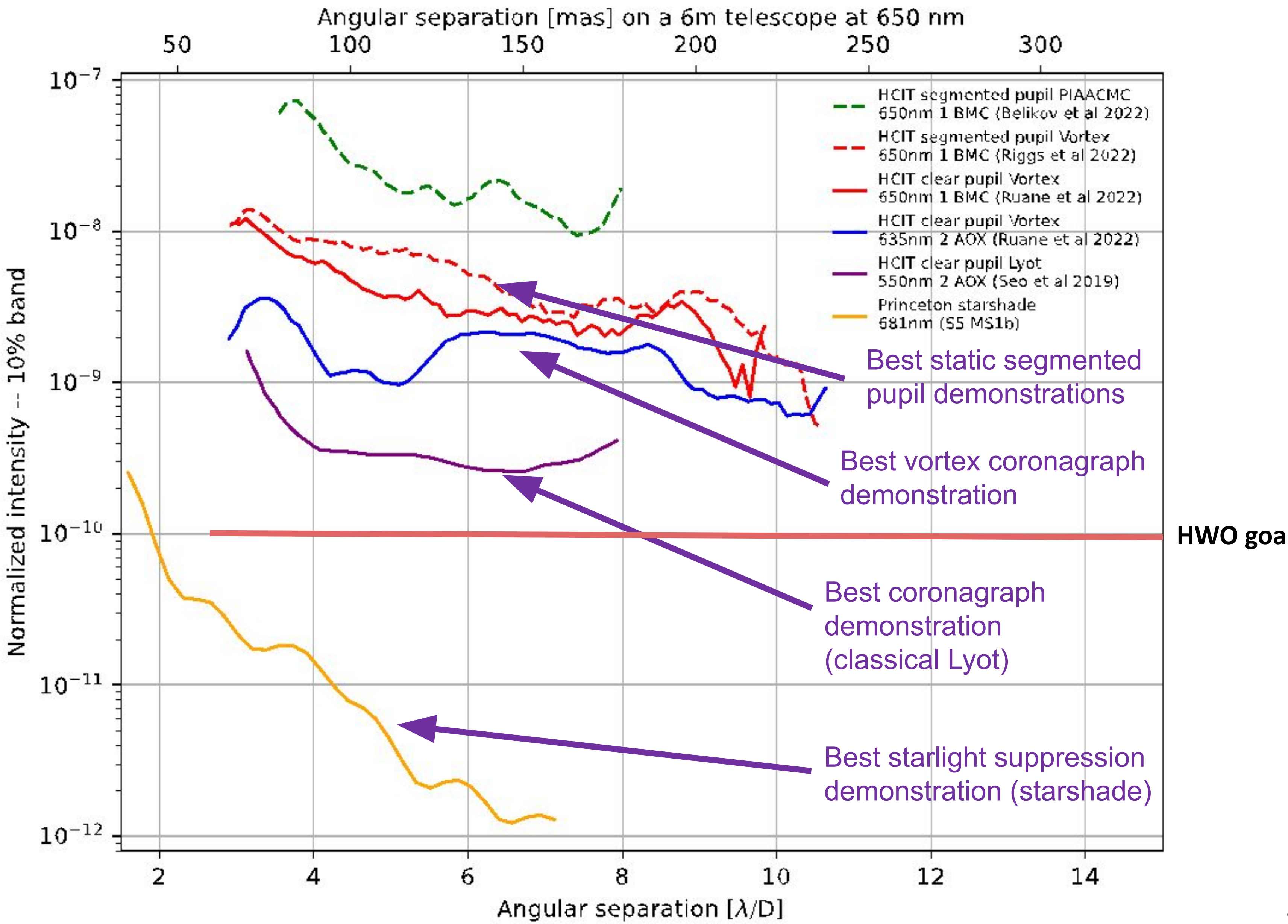
[24] WFIRST Coronagraph Testbed and Modeling Teams. *WFIRST CGI Milestone 9 Dynamic Contrast Demonstration Status Update*. https://exoplanets.nasa.gov/exep/resources/documents/ (cited on pages 14, 21).

[25] Tyler D. Groff et al. "Wavefront control methods for high-contrast integral field spectroscopy". In: *Techniques and Instrumentation for Detection of Exoplanets VIII*. Ed. by Stuart Shaklan. SPIE, Sept. 2017. DOI: 10.1117/12.2274709 (cited on page 14).

[26] David S. Marx et al. "Shaped pupil coronagraph: disk science mask experimental verification and testing". In: *Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave*. Ed. by Howard A. MacEwen et al. SPIE, July 2018. DOI: 10.1117/12.2312602 (cited on page 14).

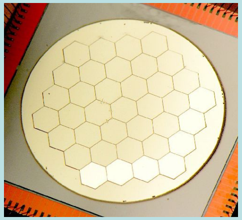
From "Progress in Technology for Exoplanet Missions"
https://exoplanets.nasa.gov/internal_resources/2595

Best Broadband Demonstrations to Date

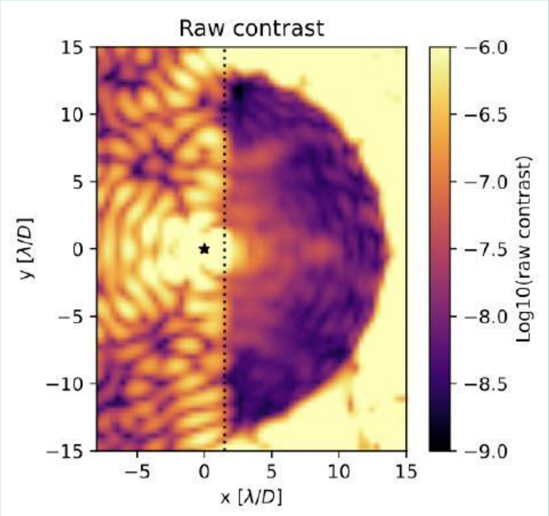


State of the Art Lab Demonstrations
(Segmented Apertures)

Soummer et al (2022): Phase-apodized Lyot Coronagraph

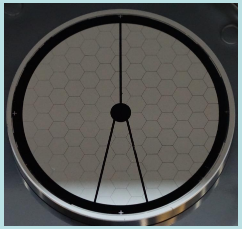


Segmented mirror simulating a segmented off-axis mirror in-air

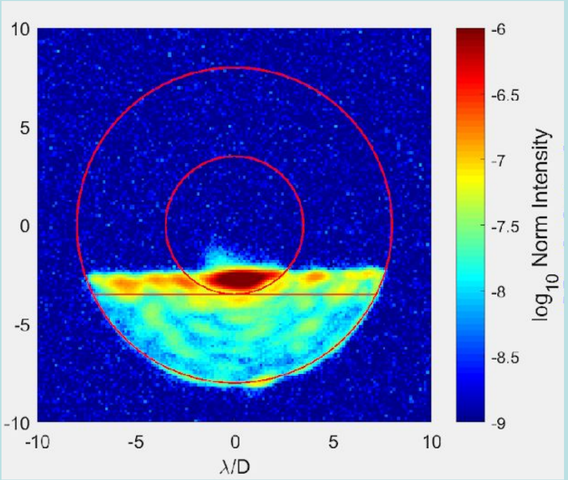


2×10^{-8} average contrast
2-13 λ/D
0% bandwidth
unpolarized light

Belikov et al (2022): PIAACMC

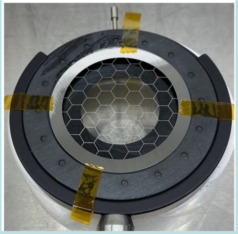


Segmented mask simulating a static segmented on-axis mirror in vacuum

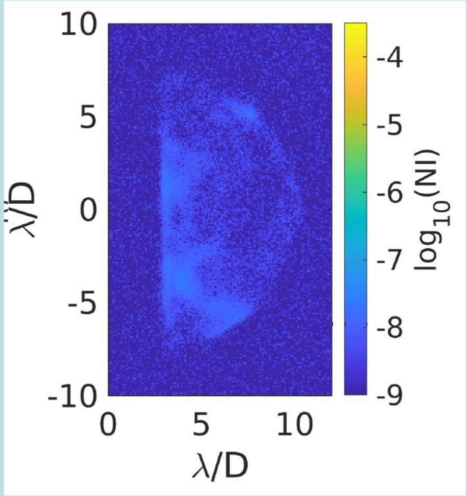


1.8×10^{-8} average contrast
3.5-8 λ/D
10% bandwidth
polarized light

Riggs et al (2022): Vortex Coronagraph



Segmented mask simulating a static segmented off-axis mirror in vacuum



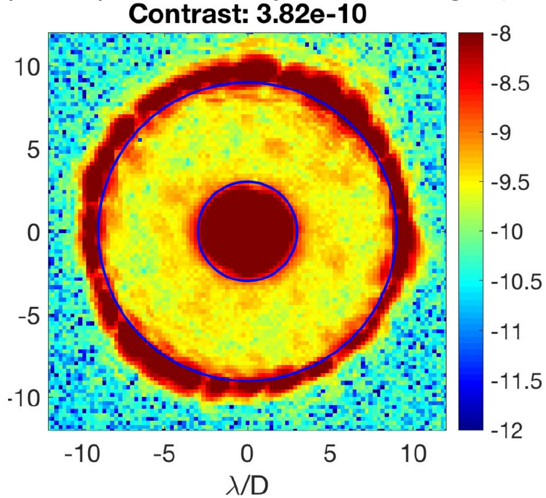
4.7×10^{-9} average contrast
3-10 λ/D
10% bandwidth
polarized light

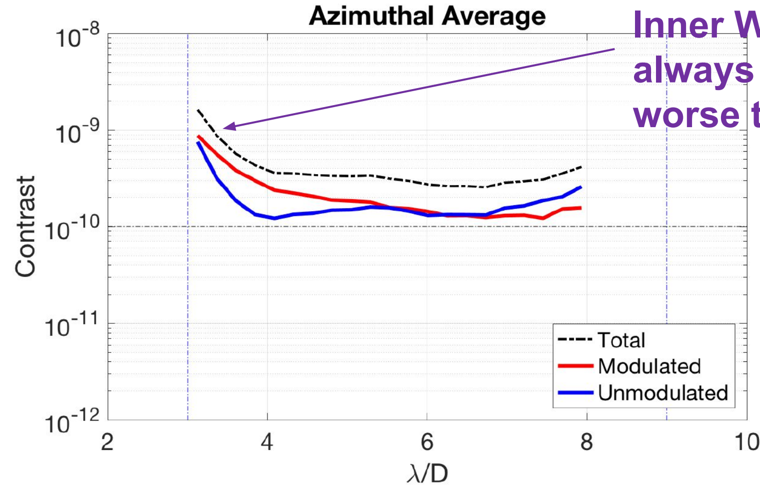
Habitable Worlds Observatory requirements
(CBE, ref. Astro2020 Table E.1)

- IWA: ~ 60 mas:
  - VVC (LUVOIR-B) design meets requirement for λ < 0.62 µm (6-meter aperture), whereas the required spectral coverage might be as wide as 0.3 – 1.8 µm
- OWA for Spectroscopy: ~ 500 mas
  - VVC (LUVOIR-B) design meets requirement for λ > 0.52 µm, whereas the required spectral coverage might be as wide as 0.3 – 1.8 µm
- OWA for Imaging Only: ~ 1"
  - VVC (LUVOIR-B) design meets requirement for λ > 1.0 µm
- Contrast: ~ 1E-10
  - APLC and HLC (LUVOIR-A) designs surpass the requirement (even for an on-axis aperture) for *average* contrast (over the stated dark zone) and *point-source* stars
  - At 3 λ/D, only the HLC (LUVOIR-A) design produces 1E-10
  - Stellar diameter (or pointing jitter) has a large impact on contrast at 3 λ/D, but much smaller impact on average contrast
  - WFE due to random segment-piston jitter is generally disastrous at 100 pm RMS but tolerable at ~ 10 pm RMS
- Bandwidth: ~ 20% or greater
- Meeting all requirements will likely require a combination of coronagraphs

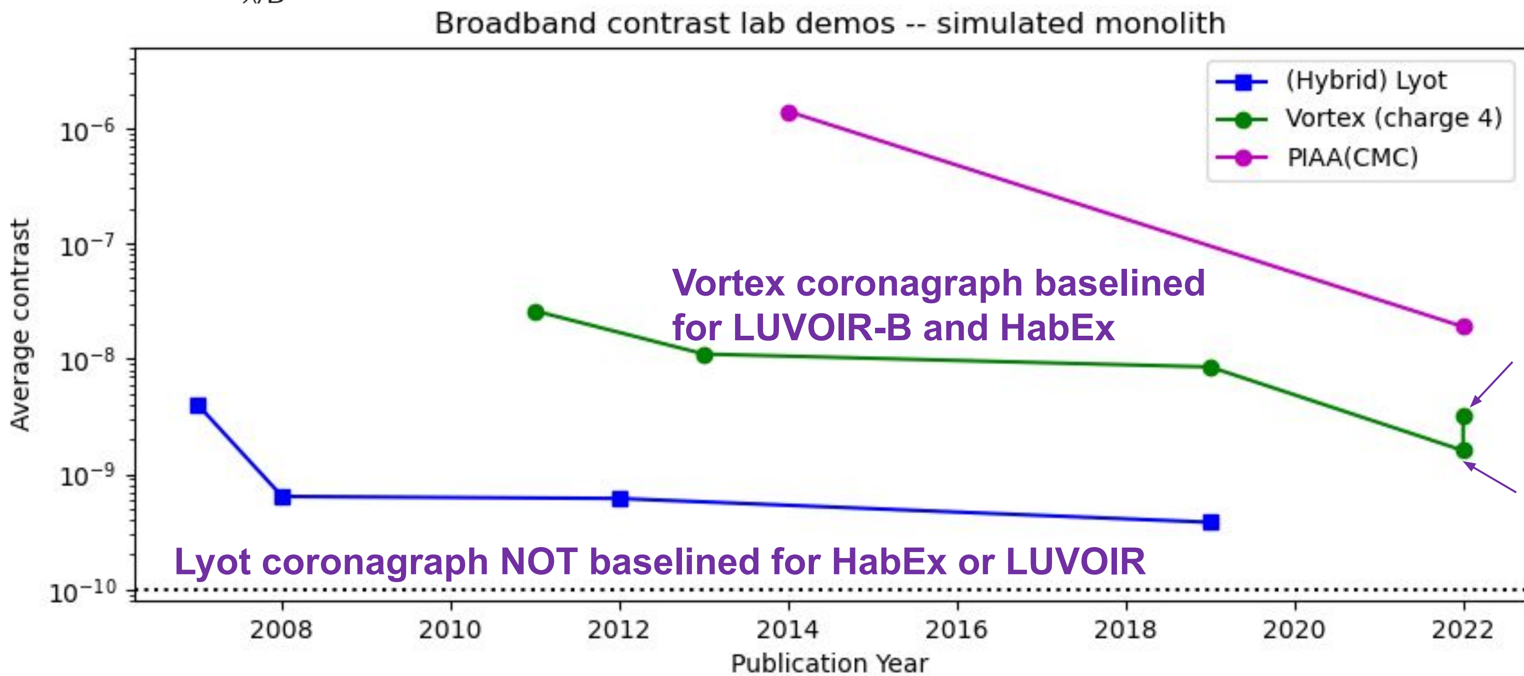
State of the Art Lab Demonstrations
(Clear Aperture)

Seo et al (2019): classic Lyot coronagraph, 550 nm 10% band: 3.82e-10 contrast





Contrast at Inner Working Angle always worse than average



Vortex coronagraph baselined for LUVOIR-B and HabEx

BMC DMs

AOX DMs

Lyot coronagraph NOT baselined for HabEx or LUVOIR

Recent Coronagraph Lab Demonstrations

Coronagraph Type	HWO goal	Classical Lyot	Vector Vortex charge 4	Phase Apodized Pupil Lyot Coronagraph	Phase Induced Amplitude Apodization Coronagraph	Vector Vortex charge 4
Aperture Type		**Circular unobscured (off-axis monolith)**		**Off-axis segmented mirror**	**Circular on-axis static segmented mask**	**Circular off-axis static segmented mask**
Deformable Mirrors	2x 96 x 96	2 AOX (each 48 x 48 act)	2 AOX (each 48 x 48 act)	2 BMC MEMs (each 1k act)	1 BMC MEMs (1k act)	1 BMC MEMs (2k act)
Separation Range	3-45 λ/D	5-13.5 λ/D (vs 3-10 λ/D)	3-8 λ/D	2 – 13 λ/D	3.5 – 8 λ/D	3-10 λ/D
Dark Hole Azimuthal Extent (deg)	360	180 (vs 360)	180	180	180	180
Mean Raw Contrast over Sep. Range	1 x 10^{-10}	4 x 10^{-10} (idem)	5.9 x 10^{-9} (1.6 x 10^{-9})	2 x 10^{-8}	1.8 x 10^{-8}	4.7 x 10^{-9}
Central wavelength (nm)	300-1300	550	635	638	650	635
Spectral bandwidth	20%	20% (10%)	20% (10%)	Monochromatic	10%	10%
Number of polarizations	2	1	1	2	1	1
Off-axis Throughput	high	medium	high	high	high	high
Sensitivity to low order aberrations	low	medium	low	medium	medium	low
Facility and Testbed		JPL HCIT-2 DST	JPL HCIT-2 DST	STScI HiCAT	JPL HCIT-2	JPL HCIT-2 DST
Vacuum Operation		Y	Y	N	Y	Y

Currently demonstrated static contrast performance degrades when moving toward coronagraphs with higher throughput and lower sensitivity to aberrations, moving from monolithic to segmented apertures, and from off-axis to on-axis

Modification of an original Bertrand Mennesson table

Recent Starlight Suppression Demonstrations

Coronagraph Type	HWO goal	Classical Lyot	Vector Vortex charge 4	Phase Apodized Pupil Lyot Coronagraph	Phase Induced Amplitude Apodization Coronagraph	Vector Vortex charge 4	Starshade subscale flight Fresnel number
Aperture Type		Circular unobscured (off-axis monolith)		Off-axis segmented mirror	Circular on-axis static segmented mask	Circular off-axis static segmented mask	n/a
Deformable Mirrors	2x 96 x 96	2 AOX (each 48 x 48 act)	2 AOX (each 48 x 48 act)	2 BMC MEMs (each 1k act)	1 BMC MEMs (1k act)	1 BMC MEMs (2k act)	n/a
Separation Range	3-45 λ/D	5-13.5 λ/D (vs 3-10 λ/D)	3-8 λ/D	2 – 13 λ/D	3.5 – 8 λ/D	3-10 λ/D	1.7-7 λ/D
Dark Hole Azimuthal Extent (deg)	360	180 (vs 360)	180	180	180	180	360
Mean Raw Contrast over Sep. Range	1×10^{-10}	4×10^{-10} (idem)	5.9×10^{-9} (1.6×10^{-9})	2×10^{-8}	1.8×10^{-8}	4.7×10^{-9}	2×10^{-11}
Central wavelength (nm)	300-1300	550	635	638	650	635	680
Spectral bandwidth	20%	20% (10%)	20% (10%)	Monochromatic	10%	10%	10%
Number of polarizations	2	1	1	2	1	1	1
Off-axis Throughput	high	medium	high	high	high	high	high
Sensitivity to low order aberrations	low	medium	low	medium	medium	low	n/a
Facility and Testbed		JPL HCIT-2 DST	JPL HCIT-2 DST	STScI HiCAT	JPL HCIT-2	JPL HCIT-2 DST	Princeton Frick
Vacuum Operation		Y	Y	N	Y	Y	N

Simulated Coronagraph Performances

Coronagraph Type	Aperture Type	Aperture [m]	λ_c [nm]	BW	IWA [λ/D]	OWA [λ/D]	Core Throughput	Average Contrast	Contrast @ 3λ/D, point star	Contrast @ 3λ/D, 1 mas star	ΔContrast @ 3λ/D due to 100 pm rms piston jitter
VVC	LUVOIR-B	8	575	10%	2.8	28	30%	5.E-10	3.E-10	1.E-09	6.E-09
APLC	LUVOIR-A	15	575	10%	3.8	12	15%	6.E-11	8.E-10	2.E-09	2.E-09
HLC	LUVOIR-A	15	575	10%	3.5	10	15%	3.E-11	1.E-10	2.E-10	3.E-09

- The table includes only coronagraphs recently analyzed by SCDA*
- The designs used deformable mirrors with 64 actuators across the diameter
- Manufacturability of the designs will be assessed (as part of the ExEP Coronagraph Technology Roadmap work)
- The table does not include all important aberrations. For example, all three coronagraphs are extremely sensitive to misalignment of the telescope's exit pupil with respect to the coronagraph's entrance pupil.
- The listed APLC and HLC are for LUVOIR-A. The LUVOIR-B aperture can enable substantially better performance (contrast/throughput/IWA). An HLC-LUVOIR-B design will be completed in FY23

*Segmented Coronagraph Design & Analysis study led by the ExEP